Definition of the Optimal Atrioventricular Delay by Simultaneous Measurement of Electrocardiographic and Doppler Echocardiographic Parameters

B. ISMER, G.H. VON KNORRE, W. VOSS, TH. KÖRBER, M. PETZSCH, J. PLACKE, C.A. NIENABER
University of Rostock, Clinic for Internal Medicine, Department of Cardiology, Rostock, Germany

Summary

Restoration of atrioventricular (AV) synchrony in cardiac resynchronization therapy of patients with chronic heart failure as well as in DDD pacing therapy of patients with AV block requires individual optimization of the AV delay pacemaker parameter. Regarding interatrial conduction and the left heart electromechanical coordination, the latter is defined by maximum stroke volume. Its total length can be defined by several methods. As a disadvantage, differentiation between the contribution of the different components is not possible. Therefore, we defined the optimal AV delay in terms reflecting the effectiveness of both, its interatrial conduction component and its electromechanical component. By this definition, the individual haemodynamically optimal AV delay at any rate can be calculated as the sum of the appropriate individual interatrial conduction interval and the left atrial electromechanical action reduced by the latency of mitral valve closure induced by ventricular stimulation. Utilization of this definition could be demonstrated by simultaneous recordings of transmitral flow velocity, telemetric pacemaker marker and the filtered bipolar esophageal left atrial electrogram by Doppler echo pattern. Only two echo screen images have to be frozen to measure the individual conduction and electromechanical components and to calculate the optimal AV delay. As an advantage, this new method provides more detailed information while the resulting optimal AV delay is in full agreement with Ritter's proposal of echocardiographic AV delay optimization which can be regarded as the current "gold standard". It can also be applied during exercise conditions. Thus, it is possible to conduct studies of several factors influencing optimal AV delay during rest and exercise.

Key Words

Atrioventricular (AV) delay, resynchronization, interatrial conduction, hemodynamics

Introduction

In atrioventricular (AV) block patients, AV synchrony can be restored by implanting DDD pacing systems if an individual optimization of the pacemaker AV delay is performed. If the latter is neglected and the AV delay is left at nominal settings, adverse hemodynamic effects may develop. Therefore, several methods were proposed to calculate or to estimate the individual hemodynamically optimal length of the AV interval [1-11]. Most of them are time-consuming and require additional techniques. Furthermore, they are limited to resting conditions. Individual AV delay optimization is an essential part in cardiac resynchronization therapy in patients with chronic heart failure and biventricular DDD pacing systems. Nevertheless, it should also be performed in any AV block therapy.

Depending on available technology, methods can be chosen based on two principles:

- An estimation of optimal AV delay which requires serial measurement of a hemodynamic parameter at several practicable AV delay steps.
- A calculation of optimal AV delay which is based on exact measurement of anly a few parameters. It should receive preference if higher accuracy is required.

Independent of the particular optimization method, the results define either an approximation or the exact total length of the individual optimal AV delay at any heart rate. Generally, this parameter is rate-dependent.

A coordination of the left atrium and left ventricle with DDD pacing in AV block patients has to consider interatrial conduction and the duration of the left heart electromechanical action. Thus, the total length of the optimal AV delay consists of a conduction and an electromechanical component. The conduction component depends on several factors among which atrial electrode position is of special interest. The electromechanical component is influenced by is influenced by the status of the left ventricle. As the total length of the optimal AV delay is related to maximum stroke volume, the differentiation between the amounts characterizing interatrial conduction and left heart electromechanical coordination is not possible. Thus, the effectiveness of both components mostly remains unknown. However, there is a basic interest in the contributions of these components. Their differentiation can be helpful during conventional DDD pacing to study factors influencing the exercise induced rate dependent shortening of optimal AV delay, in biventricular pacing to study the long-term effects of the left heart reverse remodeling and to answer in general how often AV delay has to be adjusted during long term follow-up.

To further advance the conventional methods, the study sought to define a mathematical expression of the optimal AV delay in terms of both its conduction and electromechanical basic components and to develop a method for its simultaneous measurement that can be routinely utilized.

Materials and Methods

The AV delay is a pacemaker-mediated technical time interval. It starts with a trigger which can be either

- the right atrial deflection during VDD operation or
- the right atrial pacing stimulus while in DDD operation.

For measuring purposes, the trigger can be recorded in several pacing systems by the corresponding telemetric, real-time, atrial electrogram or real-time marker channel via an analog programmer outlet in VDD and the atrial stimulus in DDD operation.

Depending on the ventricular pacing site, AV delay ends with the

- right ventricular,
- left ventricular, or
- biventricular stimulus.

Therefore, AV delay generally consists in exact definition of the optimal moment of the ventricular stimulation in relation to its given trigger.

As observed by several authors, hemodynamically optimal AV delay considerably varies interindividually. These variations are mainly influenced by interatrial conduction due to different atrial electrode locations, atrial diameters, and other factors.

To define the influence of interatrial conduction on optimal AV delay, it must be measured. While the right atrial AV delay trigger can be recorded via pacemaker telemetry, the measurement of interatrial time intervals requires an additional left atrial reference. Binkley et al. [12,13] reported an excellent correllation between interatrial conduction intervals measured against left atrial intracardiac catheter and those measured against an esophageal lead reference in normal and enlarged atria. Therefore, the combination of right atrial, telemetric, real-time electrogram or real-time sense event marker and the left atrial deflection in a filtered bipolar esophageal electrogram can be utilized for noninvasive measurements of interatrial conduction intervals. For practical purposes, real-time sense event markers are preferred to atrial electrograms [5,6]. Using this technique, interatrial conduction can easily be defined as electrocardiographic intervals between the AV delay trigger and the left atrial deflection by the (see Table 1 for abbreviations):

- interatrial conduction interval M_A-LA measured between right atrial real-time sense event marker M_A and the beginning of left atrial deflection LA in a filtered bipolar esophageal electrogram in VDD operation and by the
- interatrial conduction time S_A-LA measured between right atrial stimulus S_A and the beginning of left atrial deflection LA in a filtered bipolar esophageal electrogram in DDD operation.

Therefore, interatrial conduction intervals can be considered as the conduction component of the AV delay. This component premarily depends on conduction velocity and geometric parameters like electrode location and atrial diameter. It is a definite part of the optimal AV delay but cannot be adjusted after pacemaker implantation. Therefore, the adjustment of the AV delay must be performed within a second component. As interatrial conduction intervals are ended by left atrial deflection, the latter can also be used as a refer-

$AVD_{SENS\text{-}optimal}$	Optimal AV delay during atrial sensing (VDD operation)
$AVD_{STIM\text{-}optimal}$	Optimal AV delay during atrial pacing (DDD operation)
LA	Left atrial deflection in filtered bipolar esophageal electrogram
LAE	Left atrial filtered bipolar esophageal electrogram
$LA\text{-}MVC_{long}$	Interval between left atrial deflection in filtered bipolar electrogram and the moment of mitral valve closure during unphysiologically short programmed AV delay
M_A	Right atrial marker in the telemetric right atrial sense-event marker channel
M_A-LA	Interval between onset of right atrial marker in the telemetric right atrial sense-event marker channel and onset of atrial deflection in the filtered bipolar esophageal electrogram
S_A	Atrial stimulus
S_A-LA	Interval between atrial stimulus and onset of atrial deflection in the filtered bipolar esophageal electrogram
S_V	Ventricular stimulus
$S_V\text{-}MVC_{short}$	Interval between ventricular stimulus and the moment of mitral valve closure during unphysiologically short programmed AV delay

Table 1. List of abbreviations.

ence to define an electromechanical component characterizing the left heart electromechanical coordination. Consequently, the electromechanical component of the AV delay starts with left atrial deflection and ends with ventricular stimulus. Thus, left atrial deflection divides the AV delay into two components.

Optimal AV delay is related to maximum stroke volume. Because the left atrial contribution to the stroke volume may be reduced by ventricular stimulation that comes too early, and left atrial filling time may be shortened by stimulation that is too late, the exact moment of ventricular stimulation is of paramount importance. Its relation to the left atrial deflection defines the electromechanical component of the individual optimal AV delay. The latter allows completion of end-diastolic active filling flow prior to ventricular contraction providing the longest diastolic filling time. In other words, that the ventricular stimulus must guarantee a maximum passive left ventricular filling time without inducing premature mitral valve closure. According to Ritter's proposal [11], this condition can be determined by Doppler echo transmitral flow measurements if the end of A-wave coincides with complete closure of the

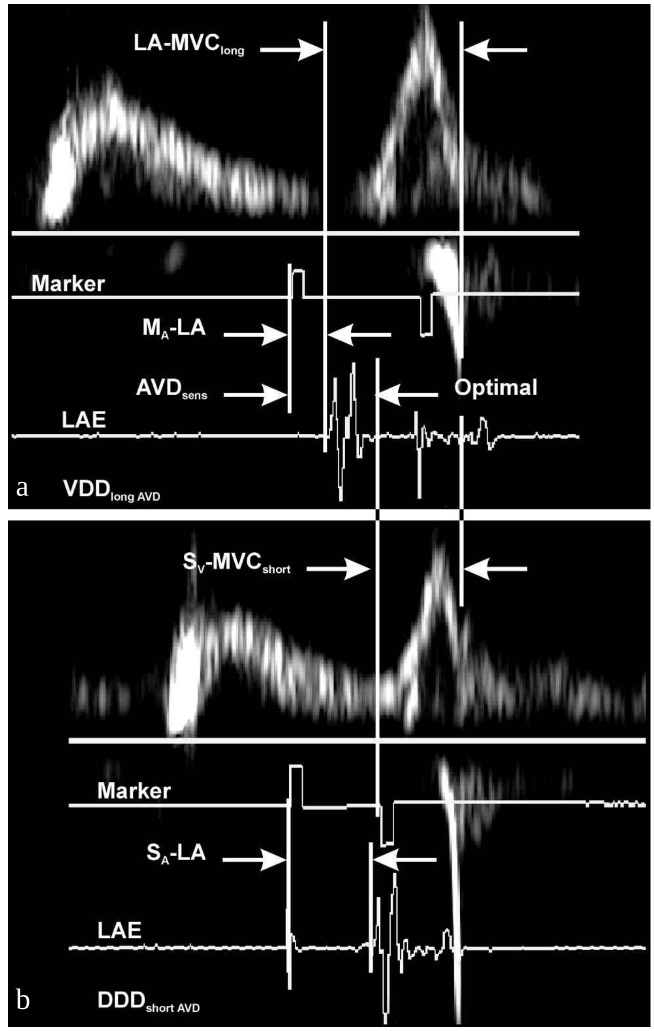

Figure 1. Simultaneaous recordings of transmitral flow, telemetric marker channel, and the filtered bipolar esophageal left atrial electrogram (LAE) in an AV block patient using a Doppler echocardiogram. Two frozen screen images a) and b) are necessary to measure all parameters to calculate the individual optimal AV delay in VDD and DDD operation.

Panel a) demonstrates measurement of the interatrial conduction component M_A-LA and the electromechanical component $LA\text{-}MVC_{long}$ during unphysiologically long AV delay (AVD_{long}) in VDD operation. The optimal AV delay in VDD operation is visualized by $AVD_{SENS\text{-}optimal}$ and results by calculating $M_A\text{-}LA + LA\text{-}MVC_{long} – SV\text{-}MVC_{short}$.

Panel b) demonstrates measurement of the interatrial conduction component S_A-LA and the electromechanical component $LA\text{-}MVC_{short}$ during unphysiologically short AV delay (AVD_{short}) in DDD operation. The optimal AV delay in DDD operation results by calculating $AVD_{STIM\text{-}optimal} = S_A\text{-}LA + LA\text{-}MVC_{long} – SV\text{-}MVC_{short}$.

See Table 1 for definition of abbreviations.

mitral walve by ventricular contraction. To define the hemodynamic component of optimal AV delay by this way, two facts must be considered:

- The left atrial electromechanical action is related to the length of the uninterrupted left atrial contraction. It can be measured as being the electromechanical time interval LA-MVC_{long} between left atrial deflection and the end of the uninterrupted left atrial contraction during unphysiologically long programmed AV delay and
- The latency of the mitral valve closure is induced by premature ventricular pacing. It can be measured as interval S_V-MVC_{short} between ventricular stimulus and its evoked mitral valve closure during unphysiologically short programmed AV delay.

These two measurements require simultaneous recordings of both the transmitral flow and a filtered bipolar left atrial electrogram by means of Doppler echo pattern. Therefore, esophageal electrogram via 4-F biolar esophageal leads (Osypka, Germany) in combination with Butterworth highpass filter ("Rostock filter", FIAB, Italy) were connected to the auxillary inputs of several echo devices. To enable the measurement of interatrial conduction intervals within the same picture, a pacemaker marker channel from analog output of a programmer (PMS 1000, Biotronik, Germany; 9790, Medtronic, USA) was also connected to a second input.

Results

Using this technique, transmitral flow, the telemetric right atrial sense event marker in VDD operation or atrial stimulus in DDD operation, respectively, and the left atrial deflection were simultaneously recorded by echo devices of different companies (ATL, USA; Hewlett-Packard, USA). Two echo screen images representing the above-mentioned conditions were frozen to define optimal AV delay in VDD and DDD pacing by its basic conduction and electromechanical component. Thus, the procedure of a detailed AV delay optimization consists of two steps:

- the measurement of M_A-LA and LA-MVC_{long} during unphysiologically long AV delay in atrial sensed operation (VDD), and
- the measurement of S_A-LA and LA-MVC_{short} during unphysiologically short AV delay in atrial paced operation (DDD).

Using these four measurements within two frozen echo screen images, the optimal AV delay was calculated as the sum of the appropriate interatrial conduction interval and the left atrial electromechanical action reduced by the latency of the mitral valve closure in relation to ventricular stimulus. With previously defined abbreviations summarized in Table 1, this can be expressed mathematically as follows:

- $AVD_{SENS\text{-}optimal} = M_A\text{-}LA + LA\text{-}MVC_{long} - S_V\text{-}MVC_{short}$ in VDD operation and
- $AVD_{STIM\text{-}optimal} = S_A\text{-}LA + LA\text{-}MVC_{long} - S_V\text{-}MVC_{short}$ in DDD operation.

Thus, performing simultaneous recordings of transmitral flow velocity, marker channel, and filtered bipolar esophageal left atrial electrogram, the optimal AV delay at any rate can be defined by its conduction and electromechanical component by taking two echo screen images (Figure 1).

Discussion

The above-mentioned mathematical expressions define the optimal AV delay at any rate in terms of its individual basic conduction and electromechanical components which are separated by the left atrial deflection. In comparison, Ritter's proposal [11], which can be regarded as the current "gold standard" in AV delay optimization, uses the same echocardiographic endpoints in relation to the ventricular stimulus. Thus, the contribution of interatrial conduction intervals is always included in the total length of the calculated optimal AV delay. However, in contrast to Ritter, the new formulas make it possible to express the contribution of the components separately. Nevertheless, as the new definition is in full agreement to Ritter's proposal, the resulting optimal AV delays calculated by the two methods are the same.

Definining the haemodynamically optimal AV delay in therms of its interatrial conduction and electromechanical components offers several advantages in understanding and programming this parameter:

- The new definitions clearly demonstrate, that the difference between optimal AV delays at any rate in DDD and VDD operation is defined solely by the difference of the interatrial conduction intervals S_A-LA and M_A-LA. This means if optimal AV delay is known either in VDD or DDD operation operation, it can be calculated for the other mode by measuring interatrial conduction intervals.

- As another result of the above-mentioned formulas, during biventricular pacing, mitral valve latency (S_V-MVC_{short}) related to premature ventricular stimulation will be shortened if interventricular conduction time decreases due to left ventricular stimulation. Thus, following the above-mentioned new equations, compared to pure right ventricular pacing, the optimal AV delay must generally be longer if biventricular pacing will be programmed.
- The method can also be utilized in biventricular pacing for detailed studies of haemodynamic and electrocardiographic long-term effects within the left heart reverse remodeling. For example, by reducing left atrial diameter, interatrial conduction time and/or left atrial electromechanical duration may also reduced. Improving left ventricular contractility may alter the latency of mitral valve closure in premature ventricular stimulation. Since all this is unknown, long-term studies of the AV delay components are of general interest to answer the question of how often the AV delay has to be controlled or adjusted during follow-up.
- Furthermore, the method enables investigation of different effects of pharmacological treatment.

Rate dependence of the optimal AV delay was reported by several authors [14,15]. Nevertheless, further detailed studies are necessary for sufficient information to clearly characterise these effects. As an advantage of both an esophageal left atrial electrogram and telemetric pacemaker signals, artifact-free recordings can be also be performed during exercise conditions. Therefore, Doppler echo investigations on a bicycle ergometer were successfully tested to design preliminary studies concerning the behaviour of both AV delay components during an exercise-induced rate increase and to define the influence of sympathetic drive in order to optimize the rate modulation of the AV delay parameter.

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Contact
Dr. rer. nat., Ing. Bruno Ismer
Department of Cardiology
Clinic for Internal Medicine
University of Rostock
PSF 100888
18055 Rostock
Germany
Telephone: +49 381 4947 708
Fax: +49 381 4947 708
E-mail: bruno.ismer@med.uni-rostock.de